HIGH PERFORMANCE LOW COST POWER CONDITIONING SUBSYSTEMS USING SMART POWER / POWER INTEGRATED CIRCUITS IN PHOTOVOLTAIC POWER SYSTEMS

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ABSTRACT

A high parts count in power conversion and control systems utilizing discrete components and a mix of discrete circuits controlled by microprocessors and ASIC's precludes realization of the highest system reliability due to high failure rate, and the highest efficiency due to various loss mechanisms. In addition, cost, weight and volume are also not optimal due to large number of discrete devices, and sometimes due to control and protection implementation schemes. Fortunately, new technologies are on the horizon that offer dramatic improvements in reliability, cost and performance of power conditioners. Such new technologies are: Smart Power (SP) and Power Integrated Circuits (PICs). With increasing voltage and current ratings and high volume production of such circuits, these technologies are the wave of the future in providing high performance low cost power conditioning subsystem (PCS) in small to large power applications. Efforts are currently underway in government and industrial organizations to realize this goal.

This paper discusses circuit designs using these devices that are suitable for PCS in photovoltaic and other industrial applications Such as electrical appliances, instrumentation, AC motor drives, battery chargers, automobiles, telecommunications, UPS, and switch mode power supplies. It examines the cost of high volume production and current technological barriers associated with the development of these technologies. Some U.S. government and international programs currently in place are presented. Currently available funding opportunities are included. Government-industry partnership activities required to promote this technology and extend it to include applications in increasingly larger systems are discussed. Currently available hardware, their ratings and manufacturers are presented. For photovoltaic applications, the concept of "AC panel" with PCS using SP/PIC hardware and mounted on the back of PV panel for large scale potential commercialization of self-contained units is being pursued in the U.S. and other countries.

It is concluded that as Smart Power technology matures, and available hardware ratings increase, the application market of these technologies will expand as a result of increasing synergism between various application sectors and decreasing production costs. In the meantime, efforts to eliminate technological barriers and to accelerate applications must continue with the help of government programs, industry investments and information dissemination.

INTRODUCTION

The conversion of free and abundantly available solar energy into cost-competitive electrical power has been the goal of many PV related efforts for over 15 years. In the post-Tesla culture AC electricity is, by far, the most common form of electrical power use in the U.S.A and in the world. Utilities have adopted AC as a standard of generation and

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' [transmission. Hence, for PV to become a significant power supplier, the DC from the PV must be converted to utility compatible AC power.

The dominant cost driver of a PV system is the PV array with its costs ranging from $4.()() to $8.00 per peak watt. The PV costs is in the range of .$.50 to $1.50 per nominal rated watt output. The other balance-of-system (BOS) costs range from $1.00 10 $4.00 per watt, again depending upon system size, voltage ratings, structure requirements, and system design. With the PCS in a critical path that directly impacts the size of the array, BOS costs, and the delivered cost of power, it is obvious that improvements in PCS performance can have a positive leveraging effect on total system size and cost.

1 [was realized that the residential utility-interactive or stand alone PV system and intermediate-size PV systems must receive full attention for large scale commercialization of PV power. It was also realized that a near-term focus must be on small PCS development. However, development of medium size PCSs is important because they arc of convenient size that can be used independently or as building blocks for larger systems. A single PCS, or multiple PCS's of this size operating in parallel, can provide power at commercial complexes or industrial plants,

Since PV power applications arc currently concentrated in small stand-alone PV systems or intermediate and residential-size utility- interactive systems, the development of low cost, highly efficient and reliable PCSs in the small to medium power range is a focal point for assuring the viability of PV systems as an alternative energy source. Current efforts in utility-interactive BOS dwell on development of residential- and intermediate- size PCS hardware.

Some new electronic component technologies have advanced to the point where they could improve efficiency and reliability of PCSs. These new technologies include PICs, smart power, ASICs, novel integrated circuit (IC) architecture, and improved packaging techniques. Some new semiconductor devices have matured to the point of being currently available for J'('S applications.

The term Smart Power refers [0 integration of power, control, protection, and sensing functions into one package. The term Power Integrated Circuit refers to monolithic structure capable of performing power switching and control functions. That is, both logic gates and power ~1111111 devices arc put on the same chip instead of building separate chips and wiring them together. Power integrated circuits are integrated over an entire wafer. Rather than making individual chips on a wafer, dicing them, and then interconnecting the.m to make a system, all the devices of a system arc integrated in one monolithic process. Logic to device drivers and high-voltage output devices are coupled. Sometimes, the terms Smart Power and Power Integrated Circuits arc used interchangeably.

A combination of high voltage and high frequency in smart power designs permits the use of digital control such as PWM control, resulting in high efficiency designs with efficiency up to 95 percent and in substantial reductions in volume and weight. In many applications where there is a need of a dedicated low voltage power supply for control purposes this requirement may be eliminated in smart power implementation. This may significantly reduce the total power system weight, volume and cost,

Smart power implementation enhances the reliability of power system because of dramatic reduction in the number of separate parts along with associated reduction in failure rate. Since PIC high voltage rating exceeds the operating voltage, the voltage margin is increased resulting in higher reliability. Reduced number of interconnections also enhances the reliability. Silicon requirements is greater in PIC implementation than that required in implementation using control chips and power conversion using discrete devices. However, this additional silicon provides the isolation between the two circuits.

In addition, with smaller size, no external parts, higher frequency, better feedback and lower production cost, the PIC implementation becomes more compact and attractive. With increasing voltage, the (II(size is larger, With increasing applications, smart power implementation is cheaper. Similarly, for higher current, the dic si7c is larger and more expensive. However, as the production quantity increases, new technologies and packaging techniques will emerge. As a result, the cost will definitely come down as in cases of other semiconductor devices (Das, R., Krauthamer, S., Bulawka, A., 1996).

MARKET OPPORTUNITIES AND DECREASING COST

As smart power technology matures and its ratings increase, the market of its applications will expand. Presently, smart power technology frnds applications in electrical appliances, instrumentation, brushless DC motors, stepper motors, flat panel displays, automatic tests equipment, avionics, printers, security systems, automobiles and telecommunications. However, terrestrial, space military and aircraft power systems will find increasing use of this technology as it matures and its voltage and c.uric.nt ratings increase. '1 his expanding market will quickly include photovoltaic systems, battery chargers, AC motor drives, robots, UPS and inverters

'1 here are many types of smart power and power integrated circuit devices for various applications. "1'heir input/output ratings are different. '1 hey are manufactured by various manufacturers. From manufacturer's data books, it is clear that hardware does exist for power conversion, control and protection, and ranges extend from low-end to high-end Of voltage and current. The trend continues towards higher ranges of voltage and current ratings, covering an increasing number of applications. Table I shows which manufacturer currently produces which type of hardware. This Table has been developed to provide an overview of the marketplace but does not necessarily cover all manufacturers.

HARDWARE TYPES	MANUFACTURER
DC/DC CONVERTERS	CALEX MANUFACTURING CO IN
INVERTER BRIDGES, HV POWER SUP., DRIVERS	COLMER SEMICONDUCTOR INC
DC/DC CONVERTERS	CONVERSION DEVICES INC
BATTERY CHARGERS	ENERGIZER POWER SYSTEM
DC/AC SOLID STATE SWITCHES, INVERTER BRIDGES	GENTRON CORPORATION
AC/DC CONVERTERS, DRIVERS	HARRIS SEMICONDUCTOR
INVERTER BRIDGES, DRIVERS	INTERNATIONAL RECTIFIER
PIC's, INVERTER BRIDGES, DRIVERS, INVERTERS	IXYS CORPORATION
DRIVERS	LINEAR TECHNOLOGY CORPORATION
BAT. CHRGRS, DC/DC CONVRTRS, REGULATORS	MAXIM INTEGRATED PRODUCTS
LOW & HIGH SIDE DRIVERS	MICREL INC
INVERTER BRIDGES	MOTOROLA
BATTERY CHARGERS	NATIONAL SEMICONDUCTOR
DRIVERS	OMNIREL CORPORATION
BATTERY CHARGERS, DRIVERS	PHILLIPS
PICS, INVERTERS, INVERTER BRIDGES	POWEREX
DC/DC CONVERTERS	POWER TRENDS
POWER POLES	SANREX CORPORATION
DRIVERS	SANYO SEMICONDUCTOR CORP
SWITCH MODE PS, DRIVERS, N BRIDGES	SGS-THOMPSON MICROELECTRONICS
DRIVERS, DC/DC CONVRTRS, BATTERY CHRGRS	TELECOM SEMICONDUCTOR
DC/DC CONVERTERS, DRIVERS, REGULATORS	TOKO AMERICA INC
POWER POLES, POWER INTEGRATED CIRCUITS	TOSHIBA AMERICA ELEC. COMPONENTS CORP
BATTERY CHARGERS, REGULATORS, DRIVERS	UNITRODE INTEGRATED CIRCUITS

TABLE 1. HARDWARE MANUFACTURED BY DIFFERENT MANUFACTURERS

Generally, the selling price/kW for various electronic products decreases with their increasing kW rating. In addition, the cost is generally lower with higher production volume. In the case of PCS hardware, it is found that the decreasing price has steeper slope for scale than for production quantity. That is, larger module sizes have lower costs per watt for the same production volume. Figure 1 shows a curve indicating economy of production volume for PCS hardware. Similarly, Figure 2 shows economy of scale (Krauthamer, S. et al, 1995), (Bulawka, A. et al, 1994), and (Bulawka, A. et al, 1994).

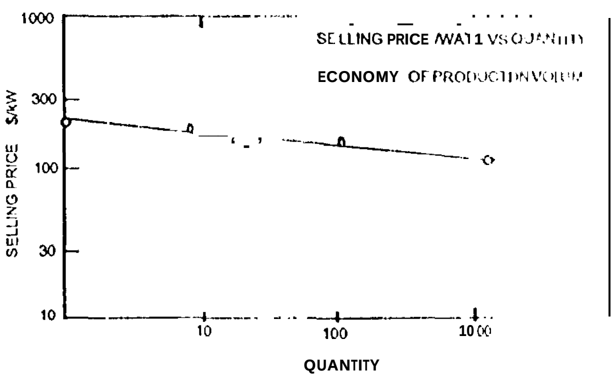

FIGURE 1. SELLING PRICE/WATT VS. QUANTITY - ECONOMY OF PRODUCTION VOLUME

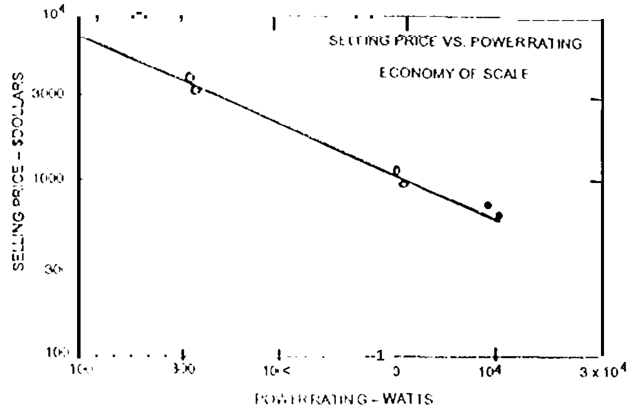

FIGURE 2 SELLING PRICE VS. POWER RATING -- ECONOMY OF SCALE

PIC technology, when fully developed in terms of ratings and isolation, will offer an opportunity to make significant improvements in cost and performance, and offer promise of meeting the U S. Department of Energy (DOE) cost and performance goals. Although the use of PICs will be initially limited to small and intermediate-size PCS, large PCS may also use them.

A typical growth pattern of smart power technology with application potential in various industrial sectors such as military and aerospace, automotive, telecommunication, electronic data processing, and industrial power and speed control is indicated in Figure 3. Needless to say, the PIC market is enormous and growing. (Smith, 1980)

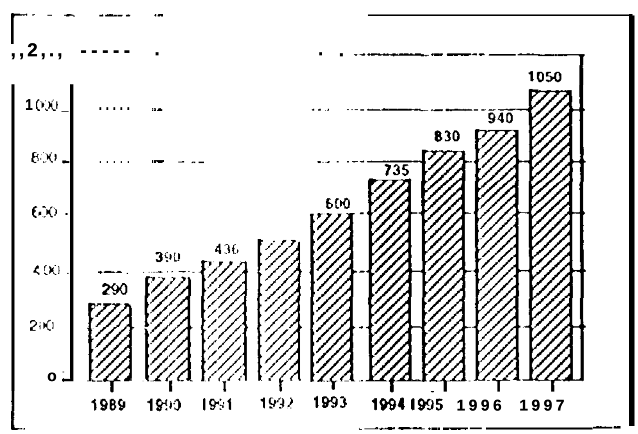

FIGURE 3. POTENTIAL SALES OF SMART POWER INTEGRATED CIRCUITS IN MILLION OF DOLLARS

U.S. GOVERNMENT ENERGY PROGRAMS

There are many activities supported by the DOE that will assist in realization of full potential of smart power technology and help meet DOE goals. For example, as part of the National Photovoltaic Program's Balance-of-System

Initiative, DOE through Sandia National Laboratory (SNL) PV Systems Applications Department funded an effort to determine the status of smart power and PIC technologies. This effort was intended to provide literature research, and evaluation of available new smart power components and PIC technologies that are applicable to PV systems and the associated PCSs.

As a result, the first workshop on smart power was held at the California Institute of Technology (Caltech) on May 20, 1987. Many presentations were made to cover both technology and applications. The workshop concluded that no real technical barrier existed that would prevent the application of smart power concepts to PV-specific systems. On addition, solutions to current reliability problems that constrain PV systems operations today may be evolved by using smart power (Krauthamer, S. et al, 1995).

Much development had occurred in PIC and smart power devices and their applications since the first workshop. Therefore, a second workshop was held on December 8-9, 1993, at Caltech. Sponsors included DOE-PV, SNL, National Renewable Energy Laboratory (NREL), Interagency Advanced Power Group (IAPG), EPRI, Power Electronics Applications Center (PEAC), and JPL. High caliber individuals from smart power manufacturers not only participated in this minimally advertised, high quality workshop, but demonstrated their enthusiasm and commitment to PV PCS developments as well.

The results of this workshop were four-fold. First, the workshop provided an understanding of the current state-of-the-art of smart power and PIC technology. Second, the strengths and technological barriers of PIC technology were identified. Third, usage of PIC technology in various PV applications was identified. Fourth, programmatic steps to further the uses of the smart power technology were identified. These are: (1) develop a plan to transfer smart power/PIC technology from smart power industry to PV PCS industry, (2) develop R&D program to identify smart power/PIC devices for integration into PV PCS units, (3) establish and maintain a current database on smart power PIC hardware, (4) plan and organize a workshop on smart power in 1995, and (5) monitor the development of a small PV AC (50W or less) modular inverter adaptable to PV modules, under SBIR and other programs (Krauthamer, S, et al, 1993, 1994).

A PCS effort currently underway and tailor-made for smart power technology is one using an integrated, nearly monolithic, PCS to further the concept of an "AC PV module". This effort is being supported by funding from the Environmental Protection Agency (EPA), SBIR, and SNL. The AC PV module concept was discussed within the DOE PV program as early as 1975, but the necessary electronics was not of age at that time. An "AC PV module" would facilitate expansion of installed PV systems and add new dimension. The idea here is to use a hybridized PCS integrated with smart power module on the panel itself for AC or DC output. A combination of high voltage and high frequency operation in smart power designs will permit the use of digital control such as PWM, resulting in high efficiency designs. Efficiencies of up to 95 percent and substantial reductions in volume and weight are obtainable. Smart power implementation could enhance the reliability of a PCS because of dramatic reduction in the number of discrete parts. Reduced number of interconnections also enhances the reliability, smaller size, no external parts, higher operating frequency, better feedback and lower production cost, enhances the reliability. Smaller size, no external parts, higher operating frequency, better feedback and lower production cost, enhance PCS smart power and PIC implementation in PCS designs. Other countries such as the Netherlands are active in advancing and using "AC panels".

The Photovoltaic Manufacturing Technology (PVMaT) project is a historic government/industry partnership to carry out research and development (R&D) in the area of photovoltaic (PV) manufacturing. PVMaT consists of joint activities between the U. S Department of Energy (DOE) and members of the U. S. PV industry. The project's ultimate goal is to ensure that U. S industry not only retains but extends its world leadership role in manufacturing and commercially developing PV components and systems.

DOD/SERDP is a joint DOE/DOD/EPA program on energy conservation/renewable resources. Fundings for 1991, 1993 and 1994 were $4,000K each year with completion projected in 2001. There are four development stages required to implement PV into a DOD application class. These are:

- Technology development
- Technology demonstration
- Application validation, and
- Implementation

Modular power processing hardware for PV applications is an objective of the Small Business Innovative Research (SBIR) program. There is a need for modular and manufacturable PCS hardware that is a multipurpose electronic converter with code-certifiable solid state AC and DC interfaces and control circuits. Larger modular sizes (50-250 kW) are needed for PV operation in conjunction with batteries, diesel generators and fuel cells for applications. The use of the state-of-the art technology such as ASICs, PLAs, and microprocessors is encouraged to promote modular designs that can use advanced automated manufacturing processes. Smaller (50-250W) PV module PCSs that operate as an integral part of available PV modules and provide an output of 120V at 60Hz of utility quality power are currently being developed. Commercialization of this development could revolutionize the PV industry by providing an "AC PV module" that has built-in maximum power point tracking and AC safety interface functions. It could essentially be an AC appliance that supplies power, and would avoid the DC-side issues of array mismatching, array utilization, and shadowing. Utility-side connections would still have to meet applicable codes but the interface would be easier with proven devices.

POWER ELECTRONIC BUILDING BLOCKS (PEBB)

The first power electronic revolution has been development of smart power and power integrated circuits. The PV development program is taking full advantage of merits of this technology in terms of size, cost and performance in an attempt to make PV power system competitive with other sources of power and used at a large scale. The second electronic revolution is currently underway in the development of power electronic building block (PEBB) at the office of Naval Reserve in the U. S. Department of the Navy. This effort is supported by the EV-DOE Program, major American manufacturers, and universities. The idea here is to shift power engineering for circuit design, systems design such that complex power electronic circuits will be replaced with a single device, development and design costs for complex power circuits will be reduced and development and design of large electric power systems will be specified. Navy is contemplating applications of such building blocks in bus transfer switches, circuit breakers, actuators, adjustable speed drivers, inverters and converters, power supplies and motor controllers. The net result of PEBB applications will be digitally controlled power, flexible system architecture, automated manufacture and reduced cost.

The PEBB essentially consists of DC-AC conversion switch, input and output filters, and required controls. Figure 4 shows a PEBB conceptual representation. Some functional details are shown in Figure 5. PEBB is going to be a challenge because of its real ability in improving controls of high currents and voltage, increasing system reliability and reduced cost. It affords use of power electronics in a wide range of applications. However, there are some technical issues related to the full-scale development of PEBB. These issues include. processing of semiconductors, MCT chips, driver and control, packaging and system integration. Certain strategies are being pursued to address these issues. These include (i) the use of concurrent research and engineering by developing components by integrating PEBB and by engineering applications (ii) development of intermediate product demonstrations by demonstrating different prototypes and by providing feedback for establishing research priority and (iii) promotion of commercialization by producing large production volumes and by demonstrating PEBB reliability. In other words, development of PEBB includes both product and process development.

U.S. Navy's efforts in developing PEBB are directed towards significant cost and performance improvements in a variety of their applications. They are taking a multi-directional approach: form research on major improvement in solid-stated switching technology, integrate SP technology into solid state switches, develop packaging technology, define system architectures for PEBBs, develop system applications and demonstrations, provide leadership for development of methods and practices in power electronics, and develop devices in consort with industry to facilitate commercial markets.

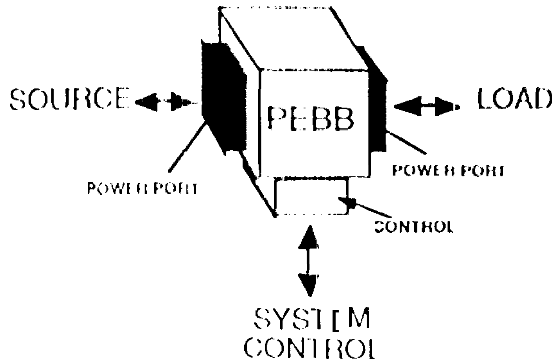

FIGURE 4 A PEBB CONCEPTUAL REPRESENTATION

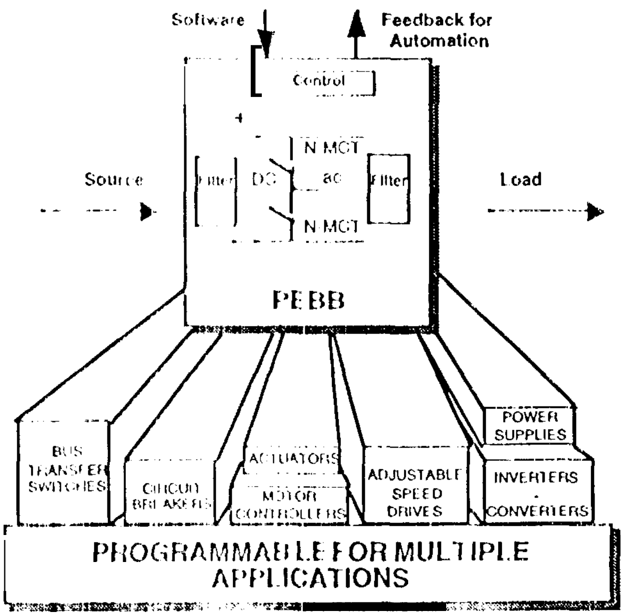

FIGURE 5. FUNCTIONAL DETAILS OF A PEBB

Apparently, there is a synergism between PEBB development effort of the U.S. Navy and Smart Power activity of U.S. Department of Energy for PV power program. The objective is the same: improvement of performance at reduced cost in various applications using power electronic power conversion. Smart power is the core of both efforts. PEBB uses the block of subsystems concept and can be used in PV systems, especially in "PV AC module". As a result of this synergism, the U. S DOE PV Program is currently participating in the PEBB as a means of supporting an R&D

effort for future PV PCS. PEBB development effort is DOE's current focus in PCS development.

CONCLUSIONS

Based on survey and evaluation of activities in the area of commercialization of PV power, some conclusions can be made. These are:

1. The cost of PCS for photovoltaic power systems using SP/PIC technologies will be decreasing with volume thereby reducing cost/kW of PV power.

2. The efficiency and reliability of PCS using SP/PIC will improve with their development and ratings

3. There is a growing synergism between government programs and within the industry. Industry is responsive and government programs encourage industry through technology transfer.

4. Development of "AC panels" in U.S. and other countries is growing. This will lead to large scale commercialization.

5. Government efforts to promote applications of Smart Power in PV applications and to stimulate activities in PEBB Program within the Government sectors and private sectors must continue.

6. Technology transfer through workshops and publications must be encouraged to stimulate new interest in PV applications and commercialization

ACKNOWLEDGEMENTS

The work described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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